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Chapman et al.

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(54) **MULTI-CHANNEL ELECTRONICALLY
SCANNED CRYOGENIC PRESSURE SENSOR
AND METHOD FOR MAKING SAME**

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patent is extended or adjusted under 35
U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/229,931**

(22) Filed: **Jan. 13, 1999**

Related U.S. Application Data

(63) Continuation-in-part of application No. 08/944,026, filed on
Aug. 25, 1997, now abandoned, which is a continuation of
application No. 08/416,596, filed on Apr. 4, 1995, now
abandoned.

(51) Int. Cl.⁷ **G01L 9/04**

(52) U.S. Cl. **73/726**

(58) Field of Search **73/708, 714, 720,
73/721, 726, 727, 719, 725**

(56)

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Primary Examiner—William Oen

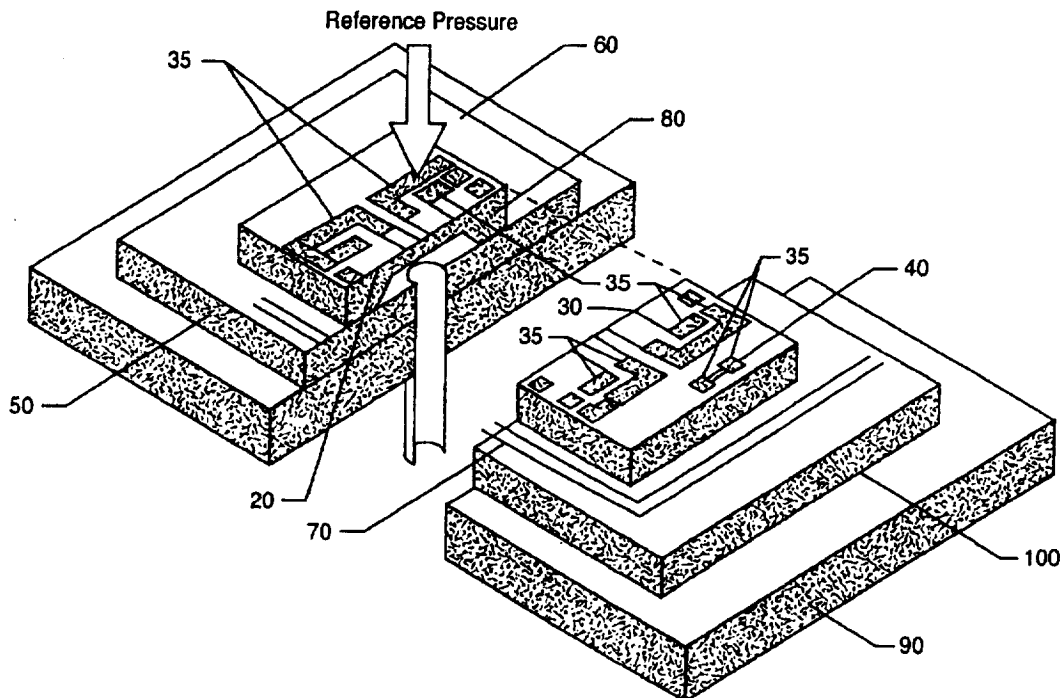
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(57)

ABSTRACT

A miniature, multi-channel, electronically scanned pressure measuring device uses electrostatically bonded silicon dies in a multi-element array. These dies are bonded at specific sites on a glass, pre-patterned substrate. Thermal data is multiplexed and recorded on each individual pressure measuring diaphragm. The device functions in a cryogenic environment without the need of heaters to keep the sensor at constant temperatures.

21 Claims, 11 Drawing Sheets



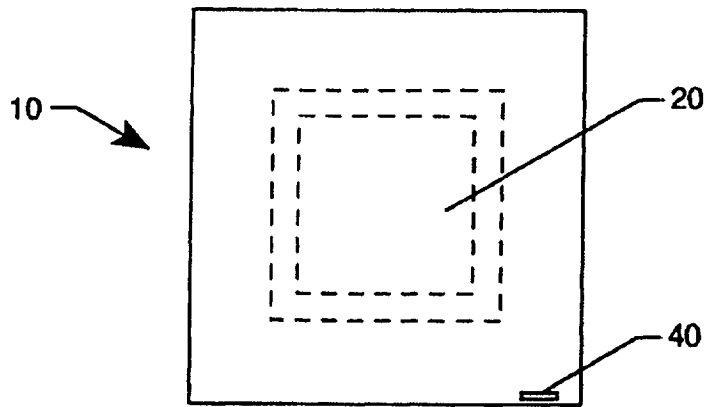


FIG. 1A



FIG. 1B

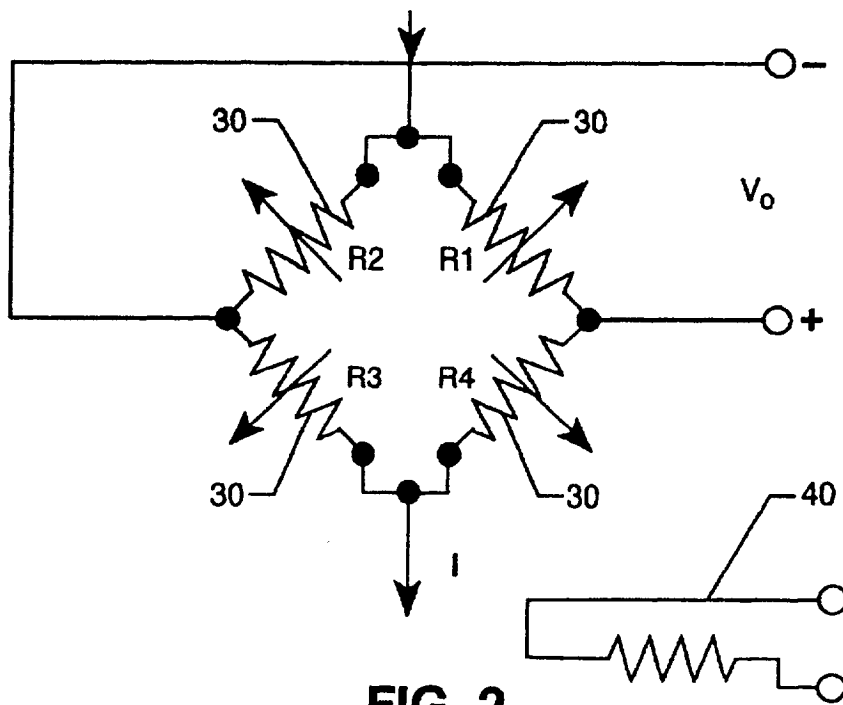


FIG. 2

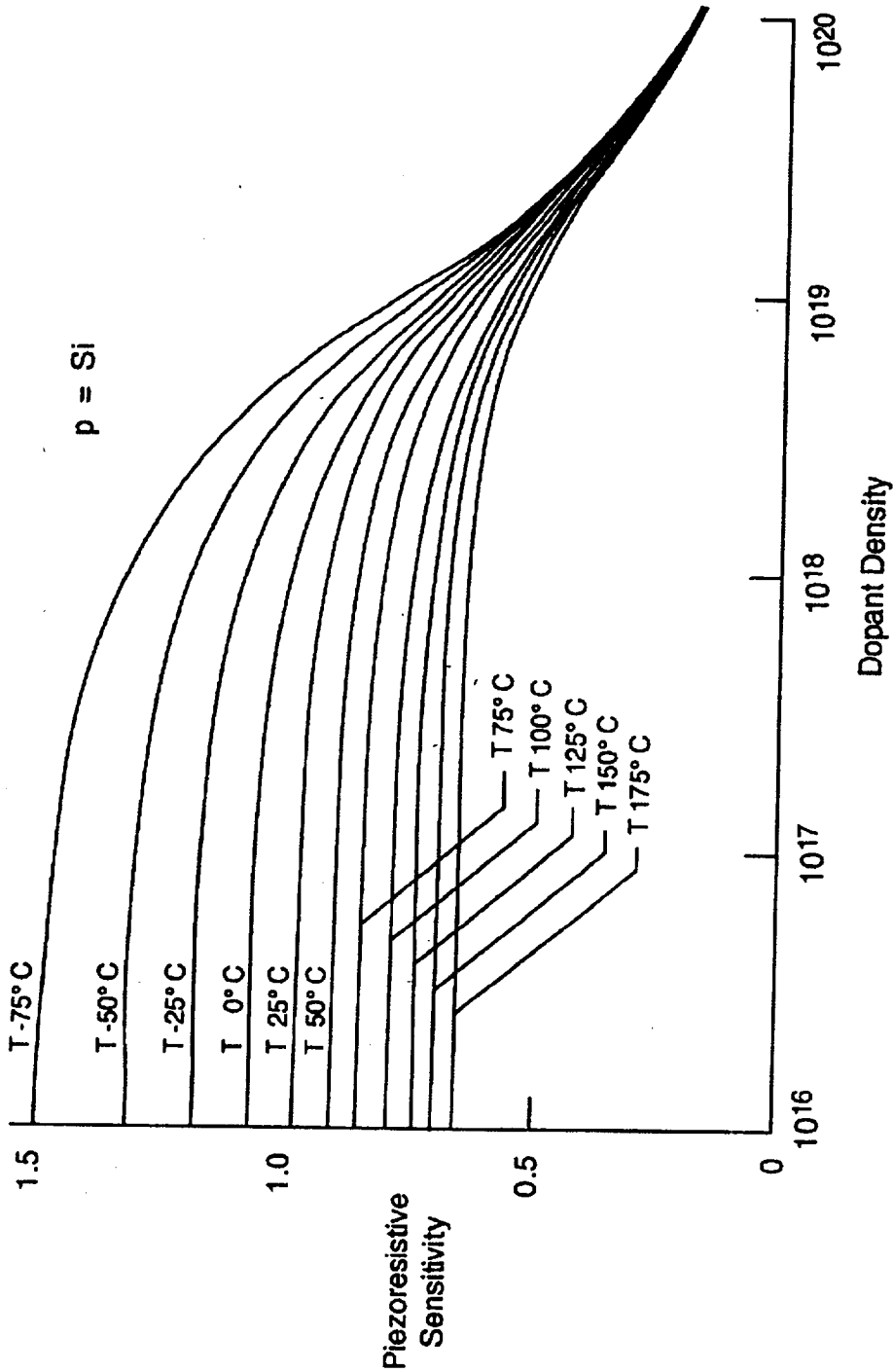


FIG. 3

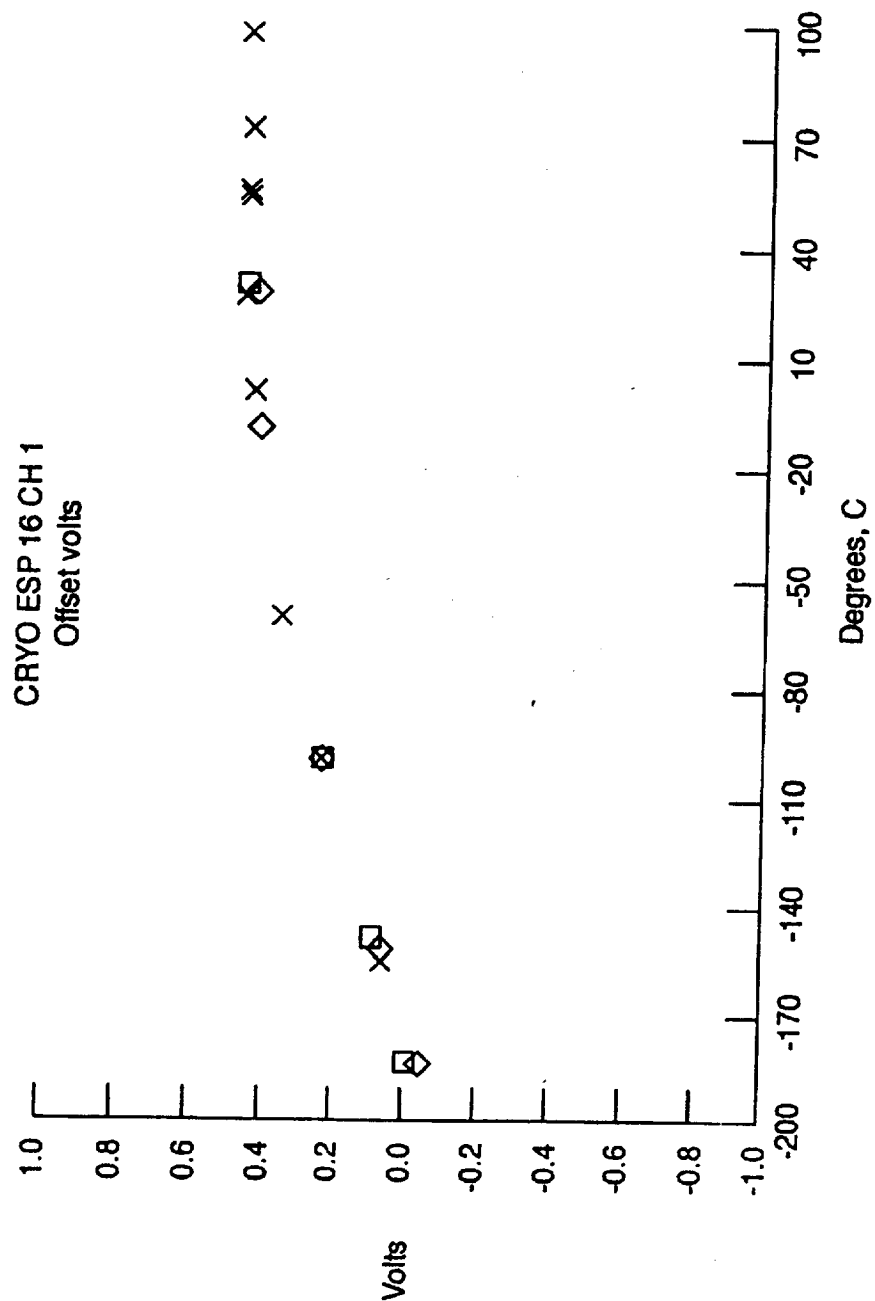


FIG. 4

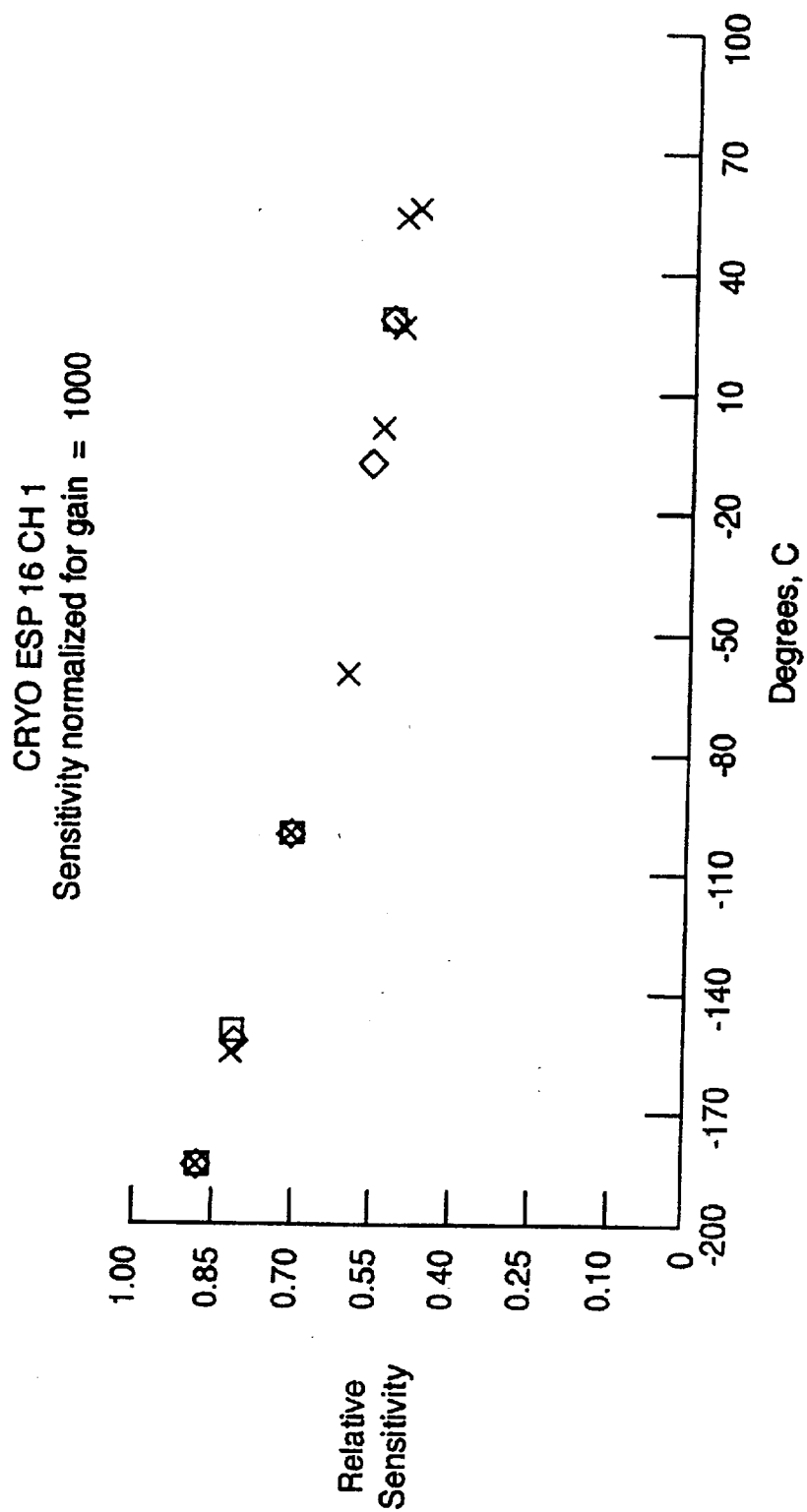


FIG. 5

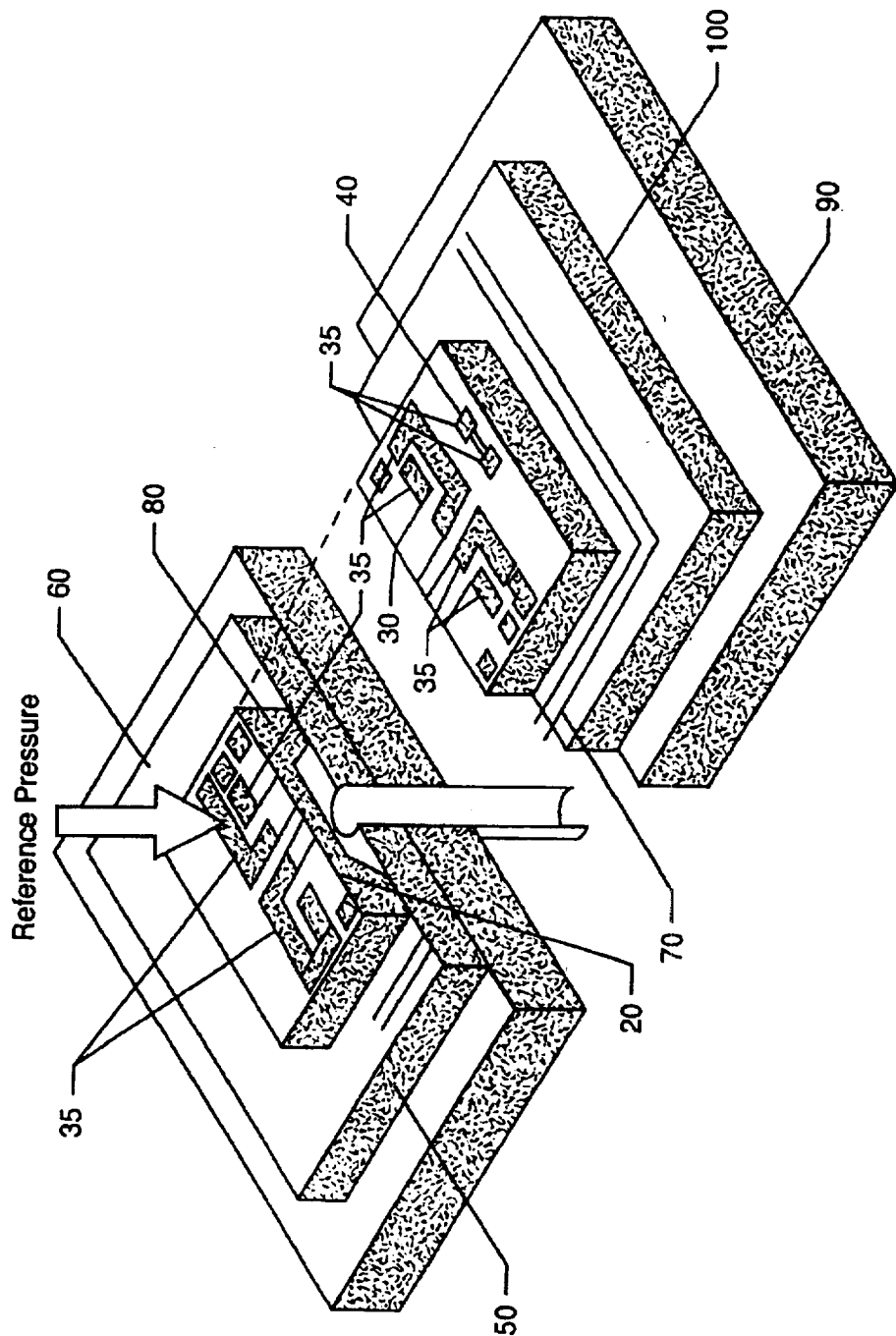


FIG. 6

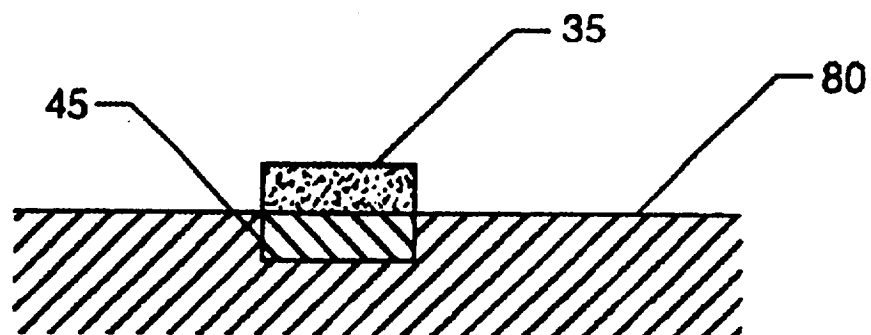


FIG. 7

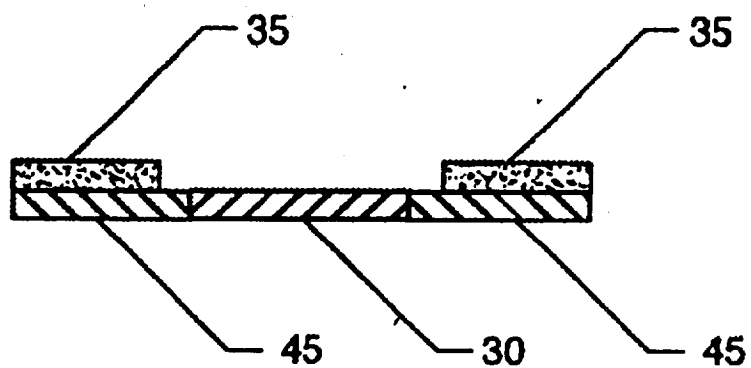


FIG. 8

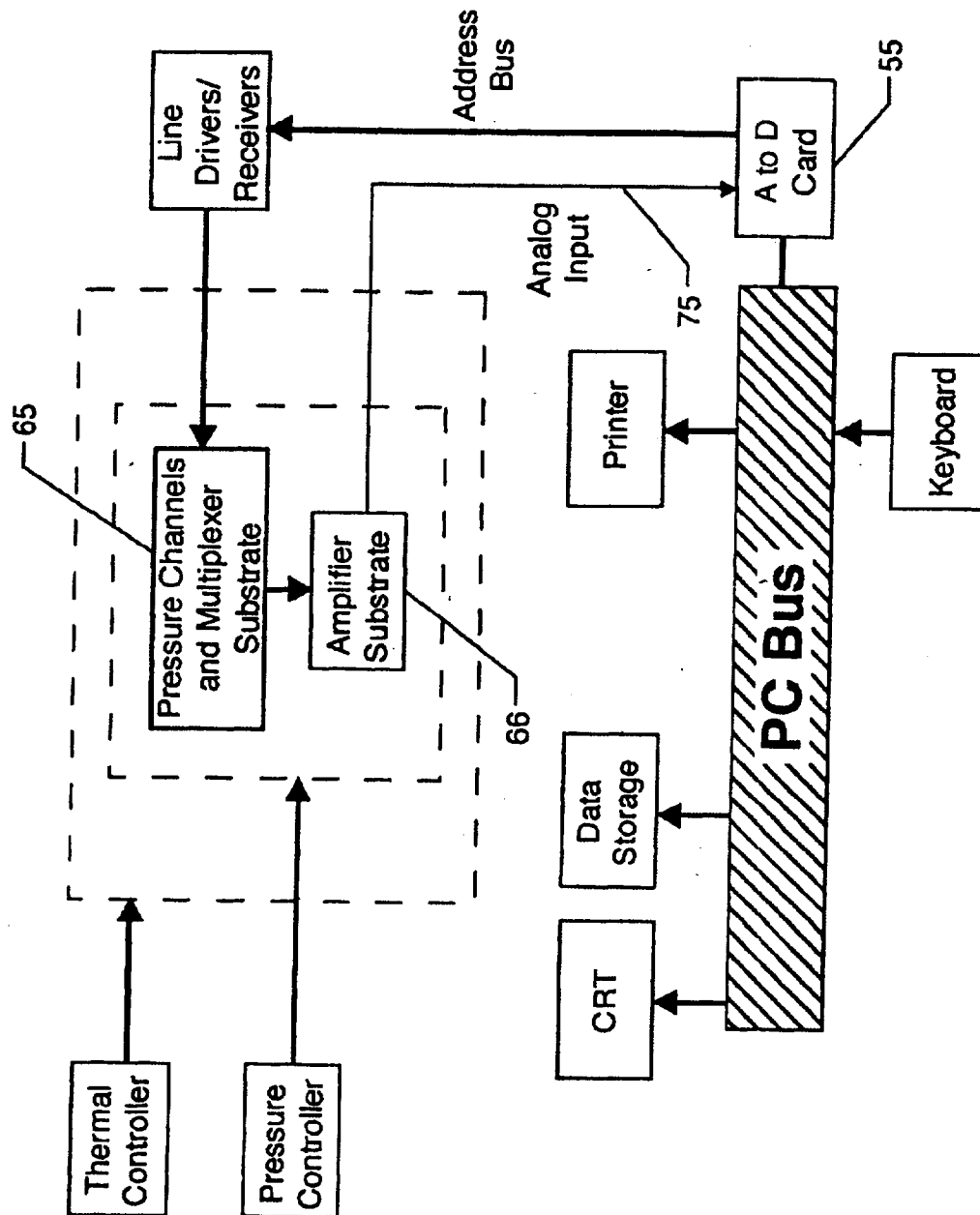


FIG. 9

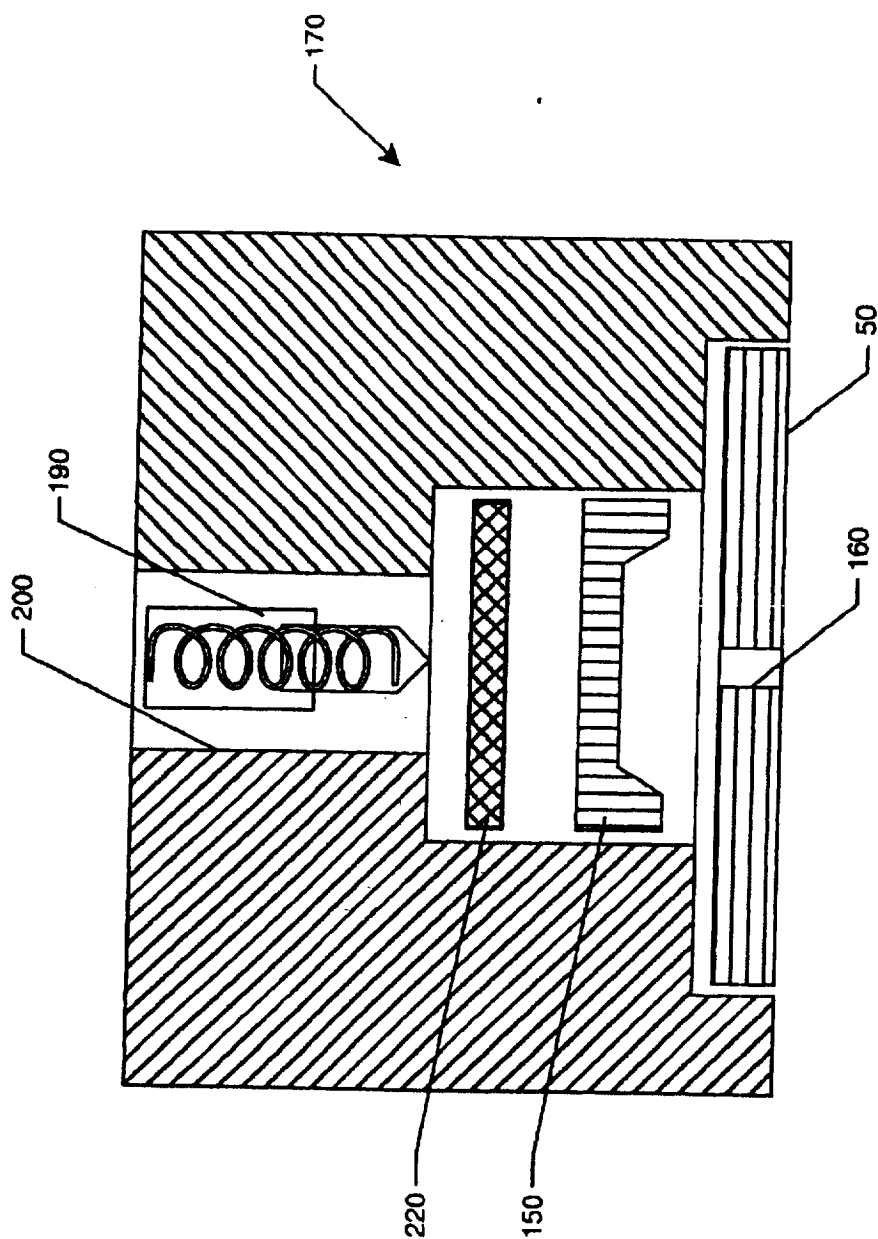
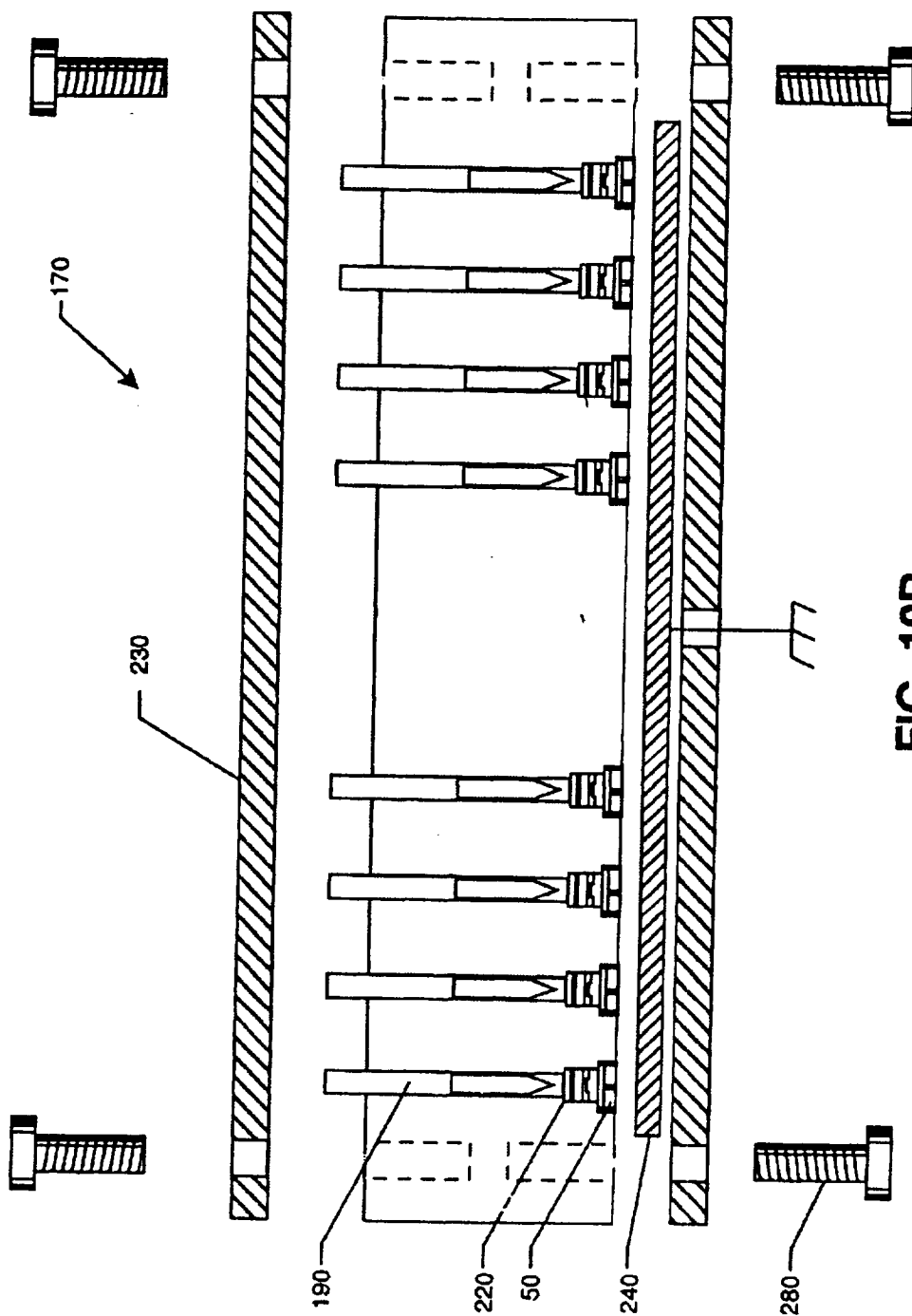


FIG. 10A



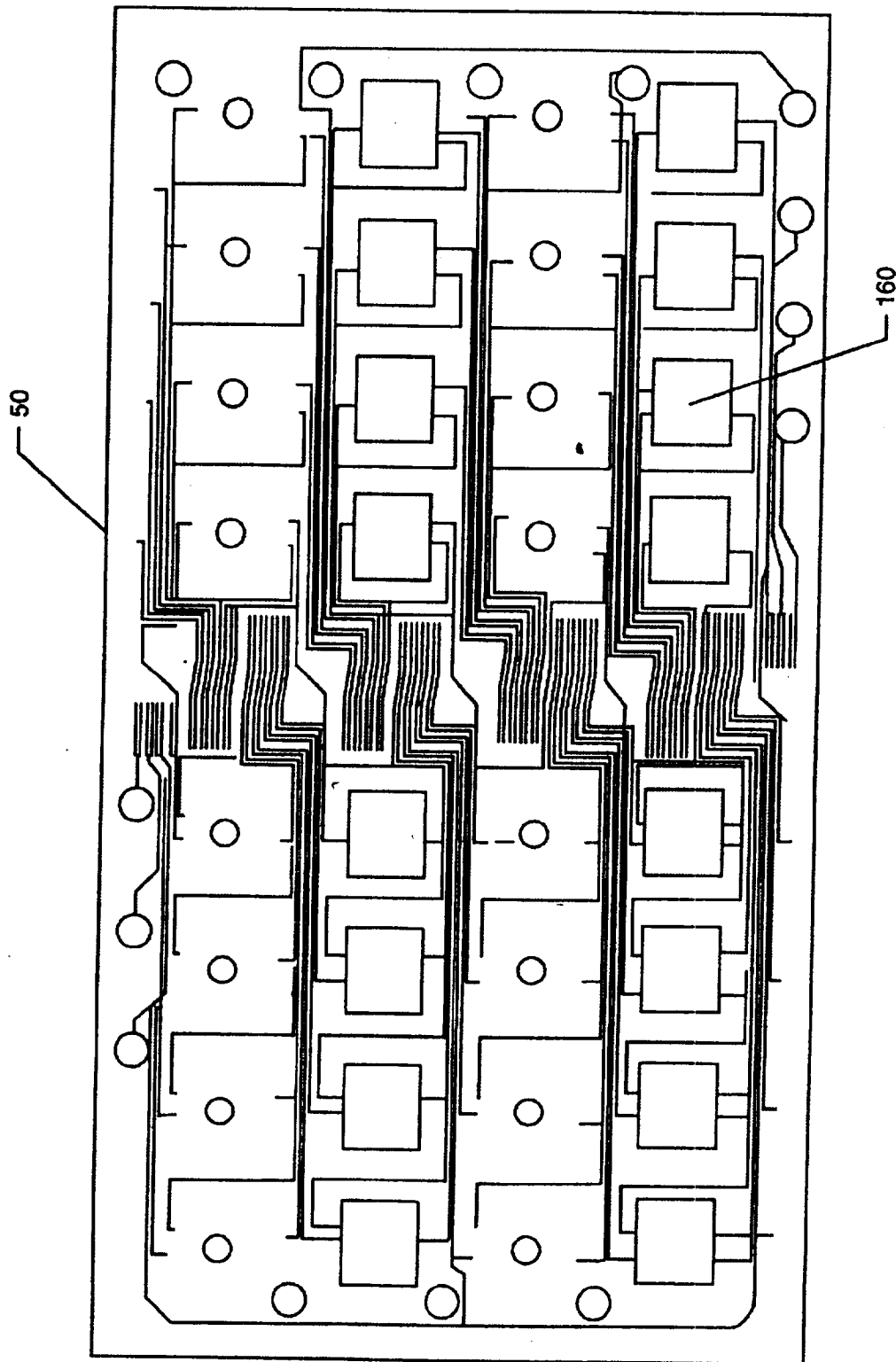


FIG. 10C

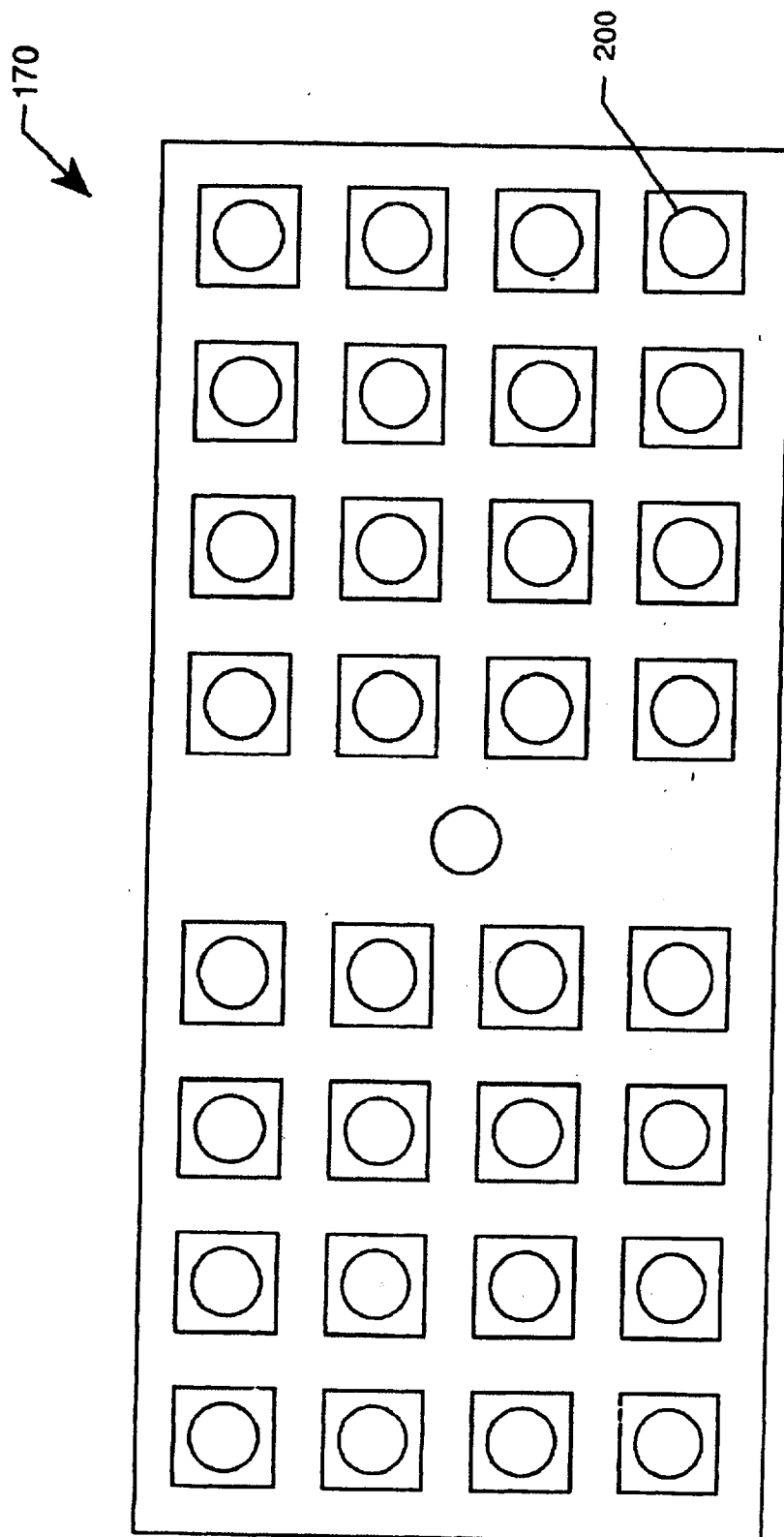


FIG. 10D

MULTI-CHANNEL ELECTRONICALLY SCANNED CRYOGENIC PRESSURE SENSOR AND METHOD FOR MAKING SAME

CROSS REFERENCE

This is a continuation-in-part application for patent application Ser. No. 08/944,026, filed Aug. 25, 1997, which is a continuation application for patent application Ser. No. 08/416,596, filed Apr. 4, 1995, both of which are now abandoned.

ORIGIN OF THE INVENTION

The invention described herein was made by employees of the United States Government and may be manufactured and used by or for the Government for governmental purposes without the payment of any royalties thereon or therefor.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates generally to a pressure sensor and more particularly to a multi-channel electronically scanned pressure sensor for cryogenic environments.

2. Description of the Related Art

There are currently 17 cryogenic wind tunnels in operation worldwide, most operate in a temperature range of -190°C . to $+70^{\circ}\text{C}$. The coldest temperature falls approximately 140°C . below the lowest mil-spec temperature for the performance rating of electronic components. In an effort to develop higher lift and lower drag airfoils, aerodynamicists are striving to study boundary layer behavior at very high Reynolds numbers. Cryogenics is used to lower flow temperatures to achieve high Reynolds numbers by increasing flow density. These low temperatures present problems with instrumentation hardware designed to measure pressure when subjected to this cold environment.

The prior art uses adhesive bonding of individual silicon pressure sensing die of silicon or Pyrex. A stress isolation pedestal may also be incorporated. An adhesive material is required to secure each sensor to the substrate. Since the adhesive exhibits a large variation in coefficient of thermal expansion (CTE) with temperature, this results in large apparent strains being exerted upon the sensors as thermal cycling occurs. Adhesive materials with critical transition temperatures above 77 K will also cause thermally induced offset variations, which will cause non-repeatability of sensor output data in cryogenic applications. This problem is more accentuated with the use of thinner membrane thicknesses necessary for accurate measurements in cryogenic wind tunnels.

OBJECTS OF THE INVENTION

It is accordingly an object of this invention to provide a device capable of performing multichannel pressure measurements at cryogenic temperatures.

It is another object of the present invention to perform the pressure measurements with increased accuracy, low noise and improved repeatability at cryogenic temperatures.

Additional objects and advantages of the present invention are apparent by the drawings and specification that follow.

SUMMARY OF THE INVENTION

The present invention overcomes the problem of measuring pressure in a cryogenic environment. This is accom-

plished by providing a miniature, multi-channel, electronically scanned pressure measuring device that uses electrostatically bonded silicon dies in a multi-element array. These dies are bonded at specific sites on a Pyrex 7740 glass substrate pre-patterned with gold circuit traces. In addition, thermal data is multiplexed and recorded on each individual pressure measuring diaphragm.

The electronics package consists of basically two parts: an amplifier circuit comprised of a monolithic instrumentation amplifier on a standard printed circuit card, and a gold circuit patterned Pyrex glass substrate comprised of pressure sensing dies and multiplexing devices. Pyrex is a trademark of Corning, Inc.

The pressure sensing device utilizes square silicon dies that have been etched on the back surface to form a very thin silicon diaphragm. The diaphragm has four highly doped (e.g., boron) piezo-resistive elements of the same geometry patterned in the diaphragm surface, two acting in compression and two acting in tension. There is also one additional bridge element on the die rim, insensitive to pressure, which provides a temperature measurement of each silicon pressure sensing die used for temperature compensation. In order for the silicon pressure sensing dies to operate properly below -100°C ., it is necessary that the dopant impurity level be on the order of 1E^{20} atoms of boron per cubic centimeter. This dopant level ensures that the sensors do not suffer from charge carrier freezeout due to low charge carrier mobility.

The requirement for structural integrity in electronic packaging is met by the use of metallic materials with low coefficients of thermal expansion such as Kovar. The coefficient of thermal expansion of Pyrex 7740 glass matches that of silicon well enough to tolerate thermal cycling in properly annealed substrates. The Pyrex substrate is first metallized with titanium/tungsten for the adhesion layer and then a layer of gold is deposited for good conduction. The circuitry pattern is then etched to produce low resistance, high quality tracks. The silicon pressure sensors are bonded to the metallized substrate by field-assisted thermal bonding. This process takes place at 375°C . It is performed under high vacuum with an applied field strength of $1\text{E}6$ volts per meter on the silicon sensors-Pyrex interface. After bonding, the sensor substrate is then attached to the tubing plate using a thin sheet of thermosetting polyamide film. The modified polyamide material remains flexible at -196°C . and provides a compliant bond between these two surfaces. The electrical interconnection of the sensor circuitry to the substrate is made using a thermo-ultrasonic wedge-ball bonding machine with substrate heating applied.

A modified, commercially available analog-to-digital converting data acquisition interface card is used to scan the pressure inputs. Since the instrumentation module is equipped with its own instrumentation amplifier and multiplexing circuitry, the interface could be streamlined by interconnecting the instrumentation amplifier output directly to the sample and hold input on the PC card with coaxial cable. This improves the signal to noise ratio since all millivolt level signal leads are contained within the instrument module and are just a few centimeters in length. Similarly, the multiplexing switches are also within the module. Linking the address and enable lines from the remote module to the timing circuitry on the PC card via line drivers and receivers ensures quiet, reliable operation. The output of the instrumentation amplifier is digitized by the A/D card in the PC. Data taken is first stored to RAM, then saved to diskette and displayed as real-time engineering units on the monitor. The data rate and sample time interval for a data record is preset by the scanning software param-

eters. The menu driven software provides for access to data files for storage, recall of sensor calibration files and for real time display.

This invention functions in a cryogenic environment without the need of heaters to keep the sensor at constant temperatures. The fabrication technique and materials used produce an instrument that will deliver repeatable data each time it is thermal cycled without recalibration. In addition, each pressure measuring component has its own temperature sensor, thereby eliminating thermal offset errors due to changing temperatures.

In addition, the advantage over existing devices is the freedom from hand mounting of each sensor and freedom from the tedious application of elastomer or adhesive bonding material to each sensor. The sensor array is one coupon, just as if it was a VLSI circuit with the sensors precisely positioned on the substrate without any trace of die attach adhesive. The application of pressure sensors to make accurate measurements is greatly enhanced due to this measure. The adhesive material necessary to attach sensors in prior art is not conducive to accurate measurements since the elastomeric material expands and contracts with temperature variations. This undesirable effect applies mechanical forces to the sensors in such a fashion as to cause drift. The main advantage of this method is in cryogenic applications. The sensors remain bonded throughout hundreds of thermal cycles and exhibit stable and repeatable calibrations for years. The accuracy of the sensors is stable and there is no need for any mechanical calibration valve apparatus within the measuring instrument.

The exact placement of the sensors will facilitate automated or manual ballbond electrical lead placement. The elastomerically bonded sensors usually have some randomness to the positioning and also have elastomeric residue present plus undesirable outgassing fumes from the curing process can cause corrosive effects on nearby components. The main advantage is in the stability. The curing process takes up to a full year to complete and this affects the measurement accuracy of the instrument since the elastomeric material induces random drift in the sensor, which cannot be accounted for by any means other than frequent recalibration, which is very costly in the case of wind tunnels. Another advantage is that the sensing module can operate accurately at cryogenic temperature and thus does not need auxiliary heaters to maintain a warm environment during wind tunnel testing. This elimination of the heating requirement while maintaining the high accuracy is a great asset since the model in which the modules reside during the test is not subject to heating effects from instrumentation within the model. This has the beneficial effect of allowing the model to remain at the true freestream temperature of the wind tunnel. Existing technology simply did not allow this, and as a result there was an unwanted disturbance of the boundary sublayer during cryogenic testing of any model equipped with auxiliary heaters.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1a is a top view of a die;

FIG. 1b is a side view of a die;

FIG. 2 is a schematic illustration of the resistor arrangement;

FIG. 3 is a graph of piezoresistance coefficient versus temperature;

FIG. 4 is a plot of offset hysteresis;

FIG. 5 is a plot of sensitivity hysteresis;

FIG. 6 is a cutaway view of a pressure sensor bonded to a substrate;

FIG. 7 is a cross-section view of a metallization track and underlying high dopant layer on a silicon die;

FIG. 8 is a cross-section view of silicon pressure die metallization tracks, underlying high dopant layer, and resistive element;

FIG. 9 illustrates the PC interface with the pressure/temperature calibration system;

FIG. 10a is a cutaway view of a portion of the fabrication fixture;

FIG. 10b is a side view of the fabrication fixture;

FIG. 10c is a top view of the substrate; and

FIG. 10d is a top view of a portion of the fabrication fixture.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The electronics package consists of basically two parts: an amplifier circuit comprised of a monolithic instrumentation amplifier on a standard printed circuit card, and a gold circuit patterned Pyrex glass substrate comprised of pressure sensing dies and multiplexing devices.

Referring to FIGS. 1a and 1b, the electronics device utilizes square silicon dies 10, approximately 2.54 mm on each side, which have been etched on the back surface to form a very thin silicon diaphragm 20, approximately 0.3 mm high. Either single crystal silicon or polysilicon can be used. Polysilicon functions as well or better than single crystalline silicon and, due to the fabrication process of polysilicon, polysilicon devices are less expensive than single crystal devices. Referring to FIG. 2, the diaphragm 20 has four highly doped (e.g., boron) piezo-resistive elements 30 of the same geometry patterned diffused in the diaphragm surface, two acting in compression and two acting in tension. There is also one additional bridge element 40 on the die rim, insensitive to pressure, which provides a temperature measurement of each silicon pressure sensing die used for temperature compensation. As illustrated in FIG. 3, in order for the silicon pressure sensing dies to operate properly below -100°C ., it is necessary that the dopant impurity level be in the range of 1×10^{19} to 1×10^{21} atoms of boron per cubic centimeter. The higher the level of boron, the greater the insensitivity to cold. This dopant level ensures that the sensors do not suffer from charge carrier freezeout due to low charge carrier mobility. The piezoresistive pressure sensors are influenced not only by the thermal offset and sensitivity shifts in the bridge resistors but also are heavily influenced by mechanical mounting effects between the die and substrate due to temperature dependent differences in coefficient of thermal expansion between the die and substrate materials, all of which contribute to the sensor overall thermal offset drift. Plots of individual sensors, mounted by the preferred method of field assisted bonding to a Pyrex 7740 substrate yield smoothly varying, repeatable offset and sensitivity curves, as shown in FIGS. 4 and 5, respectively.

The requirement for structural integrity in electronic packaging is met by the use of metallic materials with low coefficients of thermal expansion such as Kovar. The coefficient of thermal expansion of Pyrex 7740 glass matches that of silicon well enough to tolerate thermal cycling in properly annealed substrates. Referring to FIG. 6, the Pyrex substrate 50 is first metallized with titanium/tungsten for the adhesion layer 60 and then a 1.5 micrometer layer of gold is deposited 70 to provide for good conduction and to provide

